Application Note – AN1203

Sustainable Lighting – The Case for LEDs

Abstract: *LED lighting, (or solid state lighting) is a rapidly expanding market for niche lighting applications, and is now making inroads into the general lighting market. Yet LED lighting is being faced with the very same consumer criticisms that plagued the introduction of CFL's, that of poor light quality and high initial costs. If LED lighting is to become the standard in lighting, these criticisms must be addressed, along with other issues such as power quality, and compatibility with existing light fittings in order to offer superior artificial lighting both in aesthetics and energy efficiency.*

In this paper, the potential energy demand reduction that could be attained with more efficient lighting practices is described. Following that a brief look at the qualities of LED lighting is discussed, and finally, the prospects of LED lighting in the future are assessed.

The Case For Sustainable Lighting

The combustion of fossil fuels is a major contributor to greenhouse gas emission, which is cited as a major cause of climate change [1]. Electricity generation accounts for approximately 23% of Greenhouse Gas (GHG) emissions in Ireland [2]. Increasing the use of renewable resources such as wind and wave energy for electricity generation can decrease GHG emissions by displacing the use of GHG emitting fossil fuels, while ensuring that the economy is not so vulnerable to fluctuations in fossil fuel prices. Efficient energy use is also essential in any sustainable energy policy in order to slow the growth in energy demand, so that the increased utilisation of these clean, renewable energy resources for electricity generation can ease the dependence of the power system on fossil fuels. Any reduction in energy demand will also ensure that there is a better security of supply of energy resources for future generations.

In order to reduce GHG emissions and to protect security of supply, a number of key proposals related to energy generation and demand have been approved by the European Union. These proposals include a Europe-wide 20% reduction in GHG emissions by 2020 (compared to 1990 levels), as well as reducing European primary energy[1] use by 20% by 2020 (again compared to 1990 levels) [3]. An energy policy that involves both increased levels of clean energy generation as well as effective demand side management is essential in order to meet these targets.

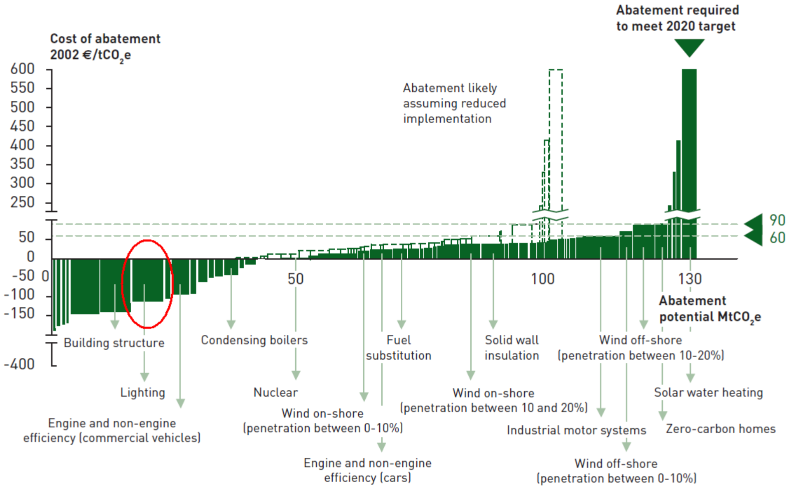


Figure 1- McKinsey UK Cost Curve [4]

---

[1] Primary energy refers to energy found in natural resources before being converted into its end-use form.

Figure 1 shows the McKinsey UK cost curve [4], a graphical representation of the monetary cost per tonne CO_2 equivalent of a number of CO_2 abatement measures that can be used to meet the 20% reduction in GHG emissions in the United Kingdom. The monetary cost of each measure is plotted on the vertical axis, while its technical CO_2 abatement potential is plotted on the horizontal axis. The curve highlights how significant the use of lighting demand side management (including more efficient light sources, occupancy sensors etc.) can be in the meeting of these targets, particularly as these measures will actually save money.

Grid-Based Electrical Lighting

The aggregated energy consumption that lighting represents means that it is an ideal target for demand side management. In 2005, 19% of all grid-based electricity was consumed by lighting, which amounts to 2,651 TWh of electricity, or slightly more than the total electricity consumption of OECD Europe for all purposes. Electricity consumption for the purposes of lighting costs end-users an estimated USD 234 billion each year [6].

Potential for Energy Savings

There is a significant potential for energy savings to be seen by utilising energy efficient lighting measures. For instance, the penetration of energy efficient CFL lighting in the residential sector to this date still remains quite low. Research has found that there is an average of only 1.5 CFL lamps in each Irish household (with each household possessing an average of 18 lighting points) [8]. This research highlights the ample opportunity that still exists to quite easily lower the 18% share of total electrical energy consumption that lighting represents in the residential sector, by using more efficient light sources [5]. A more detailed look at the potential savings per sector is shown in Figure 2 [9].

Annual Energy Use

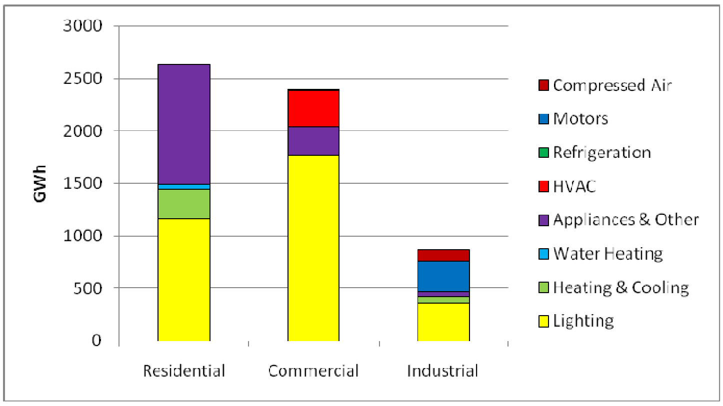


Figure 1 - Potential for Residential Electricity Savings, by End Use (GWh)

Figure 2 depicts the total economic potential for electrical energy savings in the different sectors in Ireland. The economic potential is defined as the potential energy savings under current operating conditions, due to efficiency measures that are deemed to be cost effective. In regards to lighting, this would include more efficient lighting devices, as well as other demand management solutions such as occupancy sensors and dimming controls.

The total potential for electricity savings in the residential sector amounts to 2,636 GWh per year. 44% (or 1169 GWh) of this saving can be achieved by switching to more energy efficient lighting technologies. Lighting dominates the potential electrical energy savings in the commercial sector, with 74% (1765 GWh) of the total potential electricity savings (2399 GWh per year) attainable from efficient lighting. The proportion of potential for electricity savings from lighting in the industrial sector is less than that of the commercial sector, and more comparable with that of the residential sector. The reason for this reduced share is due to the large savings that can be made from motors and other processes. Even so, 41% (359 GWh) of the total potential savings (866 GWh per year) can be saved in lighting.

That means that the total potential energy saving attributable to more efficient lighting measures is 3293 GWh per year, or 56% of the total potential savings (5901 GWh per year). With a conversion rate of 582g CO_2/kWh, [10] this equates to an annual CO_2 emission abatement of 1917 Kilotonnes of CO_2, and an economic saving of around €500 million.

Peak Power Demand Reduction

Figure 3 shows the economic potential for peak demand reduction in Ireland [9]. The economic potential for peak demand reduction is demand reduction under current operating conditions, due to energy efficient measures that are deemed to be cost effective. This peak demand is measured between the hours of 3pm and 8pm.

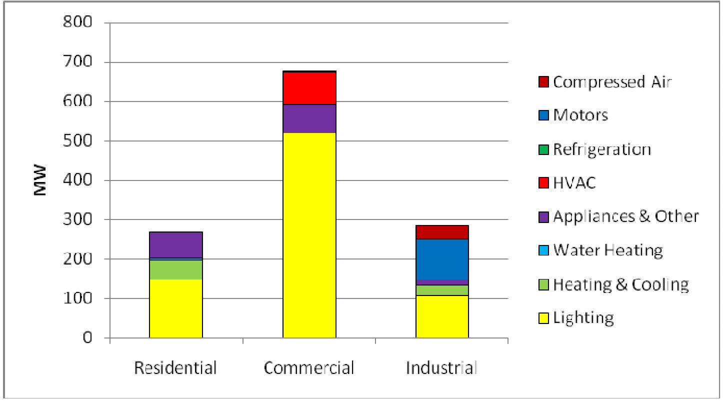


Figure 3 Potential for Electricity Peak Demand Reduction by End Use (MW)

The highest lighting demand in the residential sector occurs during this peak time of 3pm to 8pm, due to the fact that people generally arrive home from work during this period, and consequently turns on their lights. It is therefore not surprising that lightings share of the 269.3 MW total potential peak demand reduction is 55% (148.7 MW) and is greater than lightings share of potential annual savings.

Unlike the residential sector, the commercial sector has no discernable peak in lighting demand, rather it has a constant lighting load throughout the working day. It follows that there is only a slight rise in lightings share of peak demand reduction in comparison to its share of potential annual savings. Lighting represents 77% (521.5 MW) of the total potential peak demand reduction (676.3 MW).

Like the commercial sector, the industrial sector possesses no real peak in lighting demand. Therefore, lightings share of peak demand reduction is much the same as its share in potential annual savings. Lighting represents 37% (106.2 MW) of the total potential peak demand reduction (287.1 MW).

Lightings share of potential peak demand reduction for all sectors is 776.4 MW, 63% of the total potential peak reduction, 1232.7 MW.

The fact that lightings share of potential peak reduction is greater than its share of potential annual energy savings has important implications for power generation, in the way that it impacts the daily load curve.

Impact On Daily Load Curve

The daily load curve for a power system is a plot that shows how the demand changes with respect to time for any particular day. Since the electricity demand of power systems tend to follow certain predictable patterns, the fundamental shape of this curve normally remains the same from day to day, all be it with some slight variations (seasonal variations, weekday vs. weekend, sports events etc.). This curve is used by system operators in order to forecast demand, and then dispatch suitable generation plants to meet the demand.

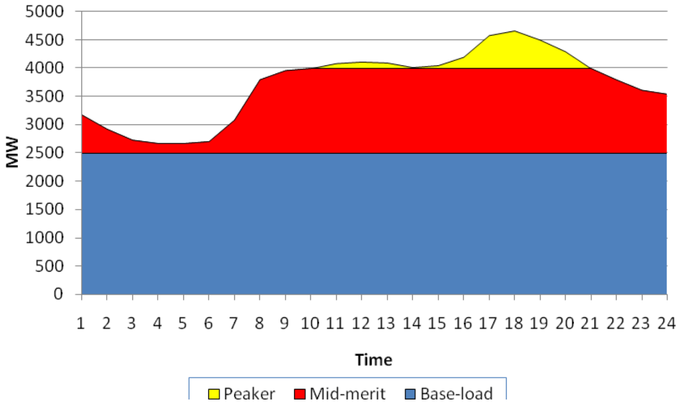


Figure 4 - Typical Plant Dispatch

Figure 4 shows a typical daily load curve[2] and plant dispatch plan of a power system. Base-load plants are plants that are designed to run constantly. They have low fuel costs, but may take many hours to achieve a steady state output. Coal and nuclear power are examples of base-load plants. Peak plants are used for short periods during times of maximum demand, and are designed to be brought online at short notice. They have short ramp up times, but tend to be more inefficient than base-load plants. Open cycle gas turbines are examples of peak plants. Mid merit plants operate in between these two plants. Combined cycle gas turbines mostly operate as mid merit plants. An efficient power system will use the inefficient peak plants as little as possible, while rarely turning off the base-load plants.

When considering the impact that energy efficient lighting will have on a power system, it is important to consider the impact it will have on the shape of the daily load curve, as well as the annual GWh savings. Due to the very nature of lighting demand, which has been shown to be greatest during the daily load peaks, a reduction in lighting demand will result in a “peak shave” (increased reduction at peaks) rather than a “percent shave” (proportional reduction along all points of load curve).

This results in an increased load factor, which is beneficial to both the electricity supplier, and the consumer. Simply put, the load factor is a ratio between the actual energy consumption during a period, and the energy that would have been consumed had the demand remained at a maximum for the same period. A higher load factor means that the more expensive peak plants need not be used as much, and the base-load and the mid merit plants can be utilised more efficiently.

An increased load factor will also decrease the number of peak plants needed, as well as the required capacity payments[3] needed to keep them online. Reduced use of inefficient peak plants also results in less GHG emissions. This all results in cleaner, more efficient electricity generation and in turn, cheaper electricity rates for the consumer. Another advantage of a high load factor is that a power system with low demand variability is more flexible, and so is more capable of dealing with the variability of renewable power resources such as wind and wave.

The load factor of a power system is given by:

$$Daily\ Load\ Factor = \frac{Daily\ Average\ Demand}{Daily\ Peak\ Demand}$$

Like electricity demand, the demand for lighting is also relatively predictable. Utilising the information for potential peak demand reduction attributable to lighting discussed earlier, and a typical seasonally adjusted lighting load curve, the impact of increased lighting efficiency on the daily load curve can be determined.

Winter Lighting Load

The potential lighting demand reduction is for winter is shown in Figure 5 (assuming that the demand reduction curve follows a typical lighting load curve [11]). The potential reduction remains at a fairly constant base-load level of around 200 MW between the hours of 12 am and 8 am. A large demand reduction (650 MW) is then seen between the hours of 9 am and 6 pm (business hours) due to increased lighting use in the commercial and industrial sectors. At around 6 pm there is a noticeable peak of around 720 MW. Here there is a crossover of lighting usage from commercial and industrial sectors, and lighting usage from the residential sector (people arriving home from work and turning on their lights). After 6 pm there is a steady drop in the potential demand reduction as people turn their lights off for the night, until it once again reaches the base-load level.

---

[2] Daily load curve on 19/12/08 (Eirgrid)

[3] Capacity payments are paid to all generators to ensure that they remain profitable to own, even though they may only be generating intermittently. This is in order to ensure that there is always enough generating capacity available to supply demand peaks and cope with plant failures.

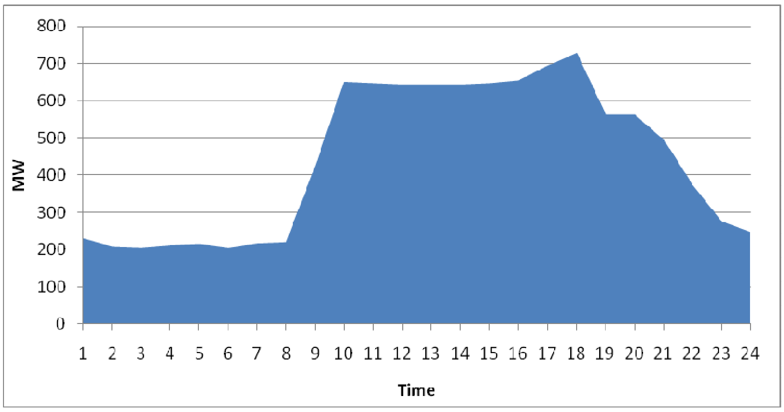


Figure 5 - Potential Lighting Demand Reduction (Winter)

Figure 6 shows the impact of this demand reduction on a typical winter daily load curve. Since the peaks of the potential lighting demand reduction curve and the daily load curve coincide, the peaks are shaved, which results in a flatter load curve. In fact the load factor increases from 0.799 to 0.835. This results in a more efficient power system with less peaking power plants needing to be dispatched.

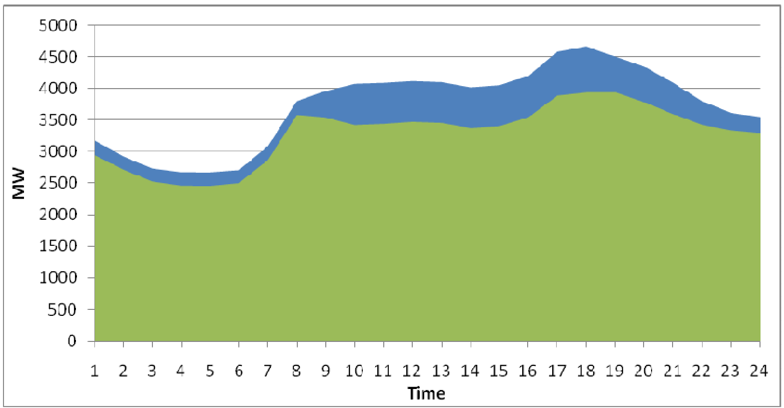
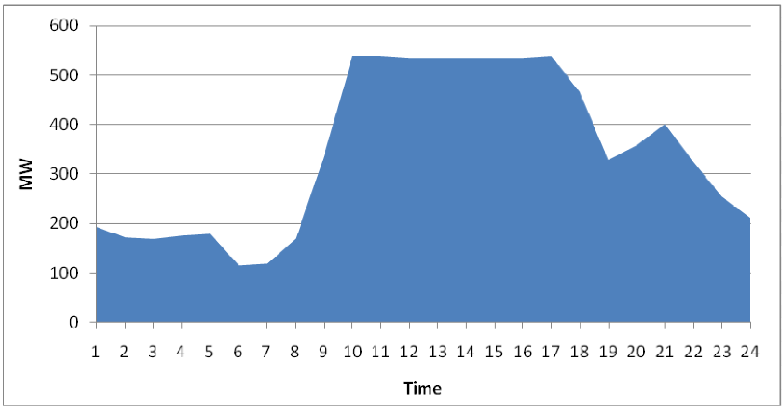


Figure 6 - Winter Scenario[4]

Summer Lighting Load

Figure 7 shows the potential lighting demand reduction for a typical summer's day (assuming that the demand reduction curve follows a typical lighting load curve [11]). There are few differences between the winter's day load and the summer's day load, which can be explained by the different sunrise and sunset times. The dip in potential demand reduction between 6 am and 7 am is due to street lighting being turned off (earlier sunrise) before the rise in demand from the commercial and residential sectors. The residential peak in demand reduction now occurs around 9 pm (later sunset), so that unlike the winter scenario there is no overlap between the commercial and residential peak demands.



---

[4] Daily load curve on 19/12/08 (Eirgrid)

Figure 8 - Lighting Load Reduction (Summer)

Figure 8 shows the effect of this lighting demand reduction on the daily load curve for a typical summer's day. Since the peaks of the potential lighting reduction and the daily load curve don't coincide to the same extent as they do in the winter scenario, the demand reduction does not improve the load factor as much. Even so, the load factor is still improved from 0.778 to 0.799.

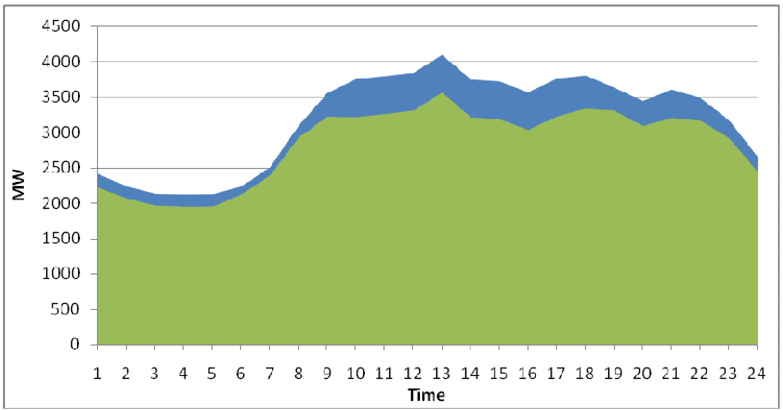


Figure 9 - Summer Scenario[5]

In conclusion, the fact that the lighting demand peak occurs at a similar time to the peak of electricity demand means that lighting is a major contributor to peak power demand. Consequently, any reduction in lighting demand results in a more efficient power system, as well as reducing the amount of energy consumed. It is for these reasons that lighting represents an ideal target for demand side management. In the next section we will discuss the role LEDs can play in sustainable lighting.

The Case For LEDs

What is Required of a Light Source?

When designing artificial light sources, it is important to remember that people require more from light than simply high lumen levels (brightness). It is necessary to consider the "quality" of the light, and its suitability for the task for which it will be used. To do this, knowledge of the spectral make up of light is necessary, particularly how light of differing wavelengths interact to generate white light.

Light is electromagnetic radiation at particular wavelengths that are that is visible to the human eye, which are wavelengths in the range of 400 – 700 nm as shown in Figure 10 below. The colour of the light depends on the wavelength of the radiation.

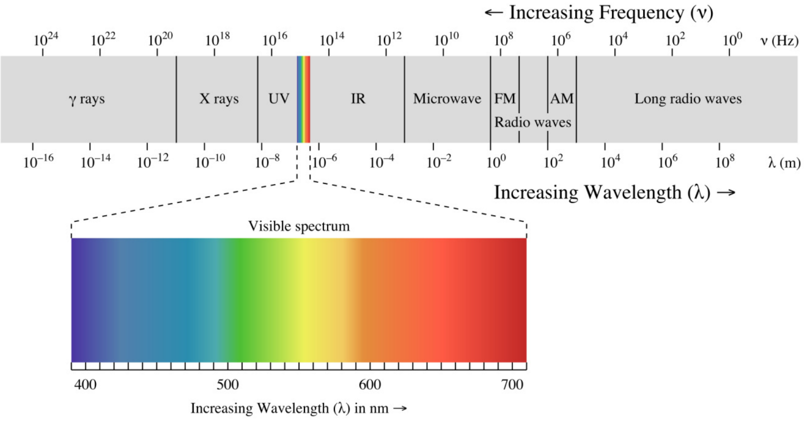


Figure 10 - Electromagnetic Spectrum [12]

White light is essentially created by mixing appropriate intensities of the primary colours of light (red, green and blue). This process is called additive mixing. The quality of the light depends on the power distribution of the

---

[5] Daily load curve on 19/08/08 (Eirgrid)

wavelengths used in creating it. The characteristics of this white light can then be described using two measurements that are referred to frequently in the lighting industry.

- Colour temperature: The colour temperature of a light source is a measure of how “cool” or “warm” the light source appears. Colour temperature is measured in degrees Kelvin (K), with cooler light (blueish-white in appearance) having colour temperatures around 5,000 K, and warmer light (yellowish-white to red in appearance) having colour temperatures closer to 3,000 K.
- Colour rendition index (CRI): CRI is a measure of how well a light source can render an objects *natural* colour in comparison with an ideal or natural light source. It is determined by averaging the measured colour shift between a test light source and this ideal light source for a set of standard test colours. CRI is measured on a scale from 0 to 100, with 100 being an ideal light source. Daylight is considered to have a CRI of 100, as do incandescent lamps.

It is important to remember that a higher CRI value is not always better. Experiments conducted at by the Lighting Research Centre at Rensaller suggest that light produced by additive mixing of red, blue and green LEDs is preferred to that of even incandescent lamps, which have higher CRI’s [13]. However, the CRI measure is useful for the classification and certification of light sources.

Spectral Power Distribution (SPD)

A spectral power distribution (SPD) curve of a light source is a depiction of the radiant power levels of the light at each wavelength (or colour) of the visual spectrum. SPD curves can prove to be very useful in quantifying the colour temperature and CRI of a light sources output.

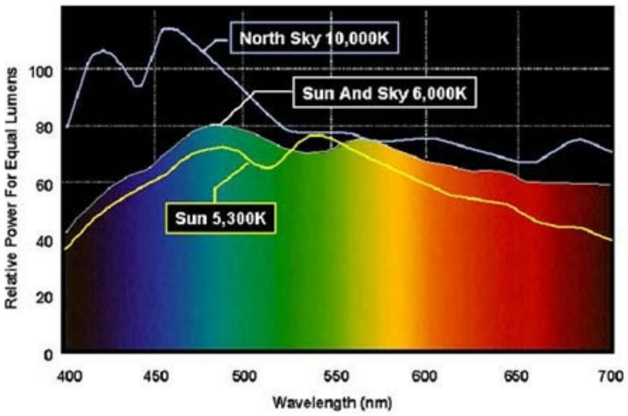


Figure 11 - Power Distribution of Daylight [14]

The spectral power distribution of daylight is shown in Figure 11. The full spectral power distribution across the entire spectrum of visible light is the reason why daylight has a CRI of 100, and the peaks in the blue and green wavelength ranges are the reason for daylights slightly cool colour temperature of around 5,300 K (depending on the time of day).

While the high CRI of daylight is highly desirable, it’s cool colour temperature is more question of personal taste, with studies showing that people prefer the warmer colour provided by incandescent lamps in living spaces, and cooler colours in workspaces [15].

Incandescent Lamps

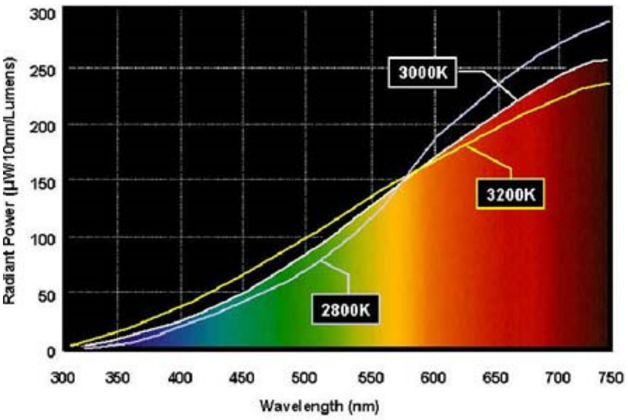


Figure 12 - Spectral Power Distribution of Incandescent Lamp [14]

Figure 12 shows the SPD of an incandescent lamp. The higher power seen in the red region of the spectrum is why the light has a warm colour. This high power continues into the non-visible region of the spectrum (infra-red). The lower power seen in the blue region of the spectrum explains why it can sometimes be difficult to distinguish between different shades of dark blue and black under incandescent lamp light.

Linear Fluorescent Lamps

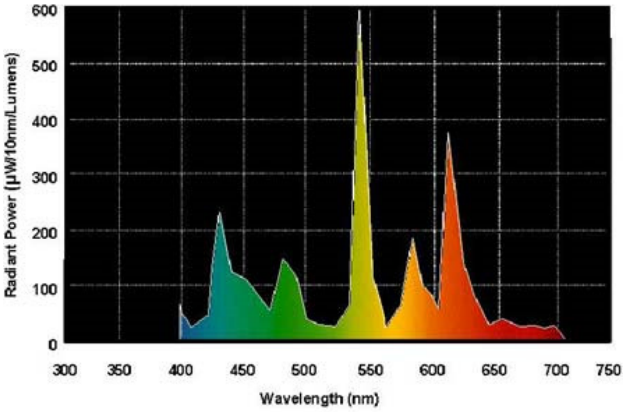


Figure 13 - Spectral Power Distribution of SPX50 Fluorescent Lamp [14]

The spectral power distribution of a fluorescent lamp is dependent on the type of phosphors used to coat the tube. An SPD of a fluorescent lamp made using rare earth phosphors is shown in Figure 13. The spikes in power that can be seen are tuned so that the fluorescent lamp has as high a CRI as is possible. Since these spikes lead to a less full spectrum than incandescent lamps, it is very difficult for the fluorescent to match the incandescent lamp's high CRI. Typical CRI values for fluorescent lamps are 65-90. The lower power that is seen in the red region of the visible spectrum leads to cooler colour temperatures.

The high efficiencies of linear fluorescent lamps, along with their long operating lives (7,500-30,000 hours) and reasonable pricing, have led to linear fluorescent lamps replacing incandescent lamps in most workplaces.

Compact Fluorescent Lamps

Due to their size and shape, CFL's can be considered to be a more direct replacement for incandescent lamps than linear fluorescent tubes. CFL's usually consist of 2, 4 or 6 small fluorescent tubes (which can be straight or coiled) mounted in a base, which is attached to a ballast that controls the current and voltage input. The SPD of CFL's are similar to that of linear fluorescent lamps (providing you are comparing lamps made with the same phosphors), so similar results for CRI (65-90) and colour temperatures (cool-white) are observed.

LEDs

Similar to normal diodes, an LED consists of the junction of a P-type and an N-type semiconductor material. When an electric field is applied across the junction, negatively charged electrons and positively charged holes are produced. These electrons and holes exist at different energy levels separated by an energy difference known as a "band gap". When an electron meets a hole, it falls across the band gap into the lower energy level, releasing the band gap energy as a photon of light with a frequency, and hence colour, that is equivalent to that band gap energy. The light that is emitted from an LED is therefore monochromatic. Since white light is made up of photons with varying wavelengths, if white light is to be attained this monochromatic light must be processed further.

Phosphors

This method involves coating LED's of one colour with phosphors of another colour in order to produce white light. Mostly this involves phosphors converting high energy blue light into lower energy colours. Examples of this method are:

- Blue LED and Yellow Phosphor: Nearly all white LED's on the market today utilise this method of white light generation. The blue light emitted by the LED excites a thin layer of phosphor, which then emits a yellow light. The mixture of blue and yellow light gives the appearance of white light. The dominance of light from the blue region of the light spectrum, and lack of light from the red region of the light spectrum means that the output from this type of light source tends to have a cold appearance, and a relatively poor CRI. This is considered to be the cheapest method to produce white light with LEDs.
- Blue LED and Several Phosphors: In this case multiple phosphors are used, each emitting a different colour when excited. When combined with the blue light of the diode, they produce white light which has a higher quality and broader spectrum than that of the yellow phosphor LED. However, the use of multiple phosphors increases the cost, and reduces the efficiency of the LED.
- Ultraviolet LED with RGB Phosphors: Ultraviolet LEDs are used to excite phosphors of red, green and blue. The resulting light has a broad wavelength and rich spectrum. Again the use of multiple phosphors increases the price and reduces efficiency.

Phosphor based LEDs have lower efficiencies than regular LEDs because of heat loss due to a phenomenon called the Stokes shift. When the phosphor absorbs a photon it enters an excited state. In order for the phosphor to relax, it emits a photon in order to lose its excess energy. If the photon emitted has less energy than the photon absorbed (as is usually the case in LED lighting), the energy is dissipated as heat energy. The difference in energy levels of the two photons is known as the Stokes shift.

White Light Creation by Mixing Colours

As has been mentioned previously, white light is created by mixing lights with different wavelengths in a process called additive mixing. Red, green, blue and sometimes amber LEDs can be used to generate light that is mixed together in order to create white light. While theoretically more efficient than the phosphor method of white light generation (no energy loss through Stokes shift), and capable of generating light with a higher CRI, it is much less popular in industry due to the larger unit area needed for the multiple LEDs, as well as the added complexity of the circuitry and optics necessary to control the blending of the colours into white light.

Another advantage of using additive colour mixing to generate white light is the flexibility of colour temperature offered by the created light by adjusting the intensity of each base colour. This flexibility raises the possibility of "tuning" the light to different colour temperatures to match the needs of the task that it is being used for.

LED Performance Characteristics

Light output and efficacy

The most efficient high brightness LEDs can operate at a luminous efficacy of over 100 lm/W. A 60 W incandescent bulb has a luminous efficacy of around 14.5 lm/W (870 lumens). In principle, a 9 W LED lamp can provide 900 lumens, which is more light than the 60 W incandescent bulb can provide. Given that the CFL equivalent of a 60 W incandescent lamp requires 11-15 W, LED lights can, in principle, also outperform CFLs.

It is important to remember that the luminous efficacy of a light source is a measurement of all of the light emitted from the source for a given energy input, and does not take into account the direction or spread of the light. Since the light from LEDs is more directional than that from incandescent lamps, it could be argued that the light from LEDs is more "useful" than that from incandescent lamps (particularly for task lighting), even if they have similar luminous efficacies.

Longevity

Since LEDs do not require a filament or cathode (which can burn out), they are much less likely to suffer from catastrophic failures than other light sources that do. Instead, the most common mode of LED failure is a gradual degradation of light output. High quality LEDs can deliver more than 70% of their initial light intensity for over

100,000 hours when operated under rated conditions [22]. This performance degradation is very sensitive to heat, highlighting the necessity for good thermal management when designing LED lamps.

The exceptionally long lifetimes of LEDs mean that the overall lifetime of an LED luminaire can be more dependent on the reliability of the driver that powers the device rather than the LEDs themselves. The main failure modes for driver circuits are degradation of the electrolytic capacitor and solder joints.

Light Distribution

As previously mentioned, LEDs are point sources of light, and so their light can be precisely targeted to where it is needed. This results in less wasted light than more multi-directional light sources such as incandescent and fluorescent lamps. While this is ideal for task lighting, it is less suited to general illumination for which a more uniform illumination on all surfaces is preferred, as well as the fact that strongly directional light sources are prone to glare.

Operation

The light that LEDs produce is directly proportional to the strength of the electric field applied across it, which means there is no warm up time or flicker. This also means that LEDs have full linear dimmability, but since the light output of an LED experiences a colour shift when the current input is changed (due to a change in band gap energy related to self-heating), pulse width modulation is the preferred method of dimming LEDs. Unlike CFLs, LEDs function very well in cold conditions, functioning in temperatures as low as -40 °C, and so are well suited to outdoor applications.

Cost

Currently, the initial cost of LED lighting is far too high for some applications, although they have become popular in a certain number of niche markets where their characteristics of long life, durability, compactness and chromatic versatility give them a competitive edge. Even though the initial costs of LEDs are very high when compared to existing lighting devices, if cost of ownership is taken into account they begin to look far more attractive.

Environmental impact and health impacts

LEDs are made from non-toxic materials and are recyclable. Unlike fluorescents they do not contain mercury, nor do they emit any ultraviolet light. Also the ability to "tune" the spectral output of RGB LEDs may make it possible to mimic the spectral shifts of natural daylight for general illumination purposes. This can have benefits such as the prevention of seasonal affective disorder (SAD) and health and productivity benefits through better matching of artificial light to circadian rhythms.

Compatibility with lighting controls

With some additional circuitry, LEDs can be made compatible with most conventional light dimmers. Also, since most off-line LED lamps already contain on-board electronics for managing AC/DC power conversion and voltage levels, adding network communications with occupancy sensors and other building management systems is made simpler.

Lifecycle Energy Costs

The primary energy required for the production of an LED lamp is about 9.9 kWh, for a CFL is about 4.08 kWh, and for an incandescent lamp is 0.61 kWh. Taking a lifecycle of 25,000 hours (as mentioned earlier an LEDs lifespan is greater than this) the incandescent lamp will have to be changed 25 times due to failure (1,000 hour lifespan), and the CFL will have to be changed 2.5 times (10,000 hour lifespan). Therefore the total production energy required for incandescent bulbs for the whole lifecycle is 15.3 kWh, and for CFLs is 10.2 kWh [24].

Far outweighing the production energy requirements of these the lamps are the primary energy required during use. For the incandescent lamp this is 3290 kWh, and 658 kWh for both CFL's and LED lamps, giving a total life cycle energy requirement for incandescent lamps of 3,305 kWh, 668.2 kWh for CFLs and 667.9 kWh for LED lamps [24]. The huge amount of energy saved during the lifecycle of both the LED lamp and the CFL when compared to the incandescent lamp more than makes up for the increased amount of energy required to manufacture a single lamp.

LEDs Future Prospects

Increase in Efficiency

The first LEDs were made in the 1960's. These early devices were only available in red and had very poor efficacies (about 0.1 lm/W) [18], and were only suitable for specialized applications such as indicators. Since then, LED efficacies have improved in line with an improvement progression known as Haitz's Law (an observation/prediction that states that the amount of light generated per LED package increases by a factor of 20 every decade) [19]. Then in 1993, the first bright blue LED prototype was developed [7]. This now meant that white light could now be created when used in conjunction with phosphors (High Brightness Light Emitting Diodes (HBLEDs)). The use of HBLEDs for lighting applications has the potential to revolutionize the lighting industry due to their excellent durability and energy efficiency.

Figure 14 shows the U.S. Department of Energy's roadmap of expected improvement in LED efficacies to 2030 [20] compared to current artificial lighting efficacies [21]. In recent years LED efficacies have surpassed that of incandescent light sources, and are now comparable with that of CFLs. The U.S. Department of Energy and manufacturers of LED lighting have set a target of 150 lm/W for high CRI LEDs by 2020, which would be ten times as efficient as incandescent lamps, and two and a half times as efficient as CFLs.

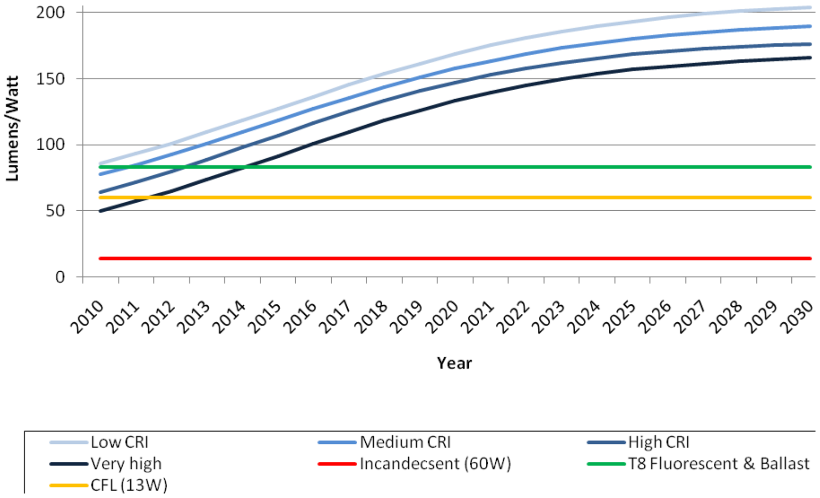


Figure 14 - LED Efficacy Roadmap to 2030

Reduction in Cost

Figure 15 shows the roadmap for initial cost per kilolumen for LEDs to 2030, as published by the U.S. Department of Energy [23], compared to the current price per kilolumen of existing artificial lighting options [21]. It is predicted that the initial price of LED lamps will not be competitive with conventional technologies until 2020 onwards.

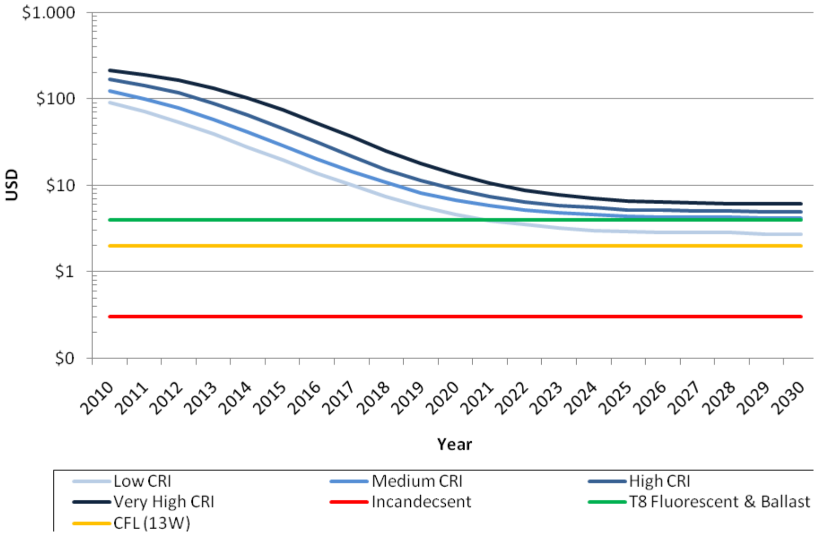


Figure 15 - Cost Of LEDs per Kilolumen to 2030

Lessons to be Learned

In spite of CFL's high efficacy and durability (rated for 5,000 to 25,000 hours), their market penetration in the residential sector has been limited to date. There are a number of reasons for this, and indeed, lessons to be learned for LED lighting technology.

- Initial cost: The initial retail price of a CFL in the 1980's was $25 – $30 USD, far more than the average consumer was willing to pay [16]. Since then, CFL prices have steadily decreased to about three to four times the price of an incandescent lamp. This lower price still remains a barrier though due to the fact that bulbs are seen to be a disposable item, and the cost of the energy used during their lifetime is not generally considered upon purchase. It is important that consumers are educated to the fact that an LED lamp cannot be considered as a disposable item in the same way that incandescent are (through the use of literature, warranties etc.)
- Perception of Lighting Quality: The first CFL's had many undesirable attributes such as a slow warm-up time, low CRI, an inability to dim and an artificial blue tint to the light. Although each one of these attributes has improved in the intervening years, CFL's still retain a stigma of having a poor lighting quality when compared to incandescent lamps. It is very important that low quality LED lighting is not allowed to give LED lighting a poor reputation (through the use of literature and information provided by standards houses such as Energy Star, directly marked on the fixtures packaging).
- Mercury Content: Every CFL bulb contains about 4 mg of mercury [17], a highly toxic cumulative heavy metal poison. This presents a problem when it comes to the disposal of the bulb. While retailers will take back CFL's as part of the Waste Electrical and Electronic Equipment (WEEE) directive, it is likely that many bulbs will find their ways into incinerators and landfill sites, where the mercury that they contain can enter the atmosphere or leech into waterways. LEDs do not have to contend with this problem.
- Quality of Product: As with powering any electrical component, operating outside the recommended parameters of LEDs will shorten their lifespan, as well greatly increasing the heat that must be dissipated by each one. However, there may be an argument for doing so when powering LED lamps. The lifetime of LED lighting devices is exceptionally long when compared to other lighting options.

One method of alleviating this problem is to make the initial cost of the LED lamp as cheap as possible, at the expense of the overall lifespan of the device. A way of doing this is by reducing the number of LEDs used in the design (the most expensive component) and increasing the light emitted by each LED by increasing the current flowing through each one. This of course will shorten the lifespan of the device, but will lower the initial cost. The problem with this is that some manufacturers my go overboard with this concept, drive the LEDs far too hard, and the LEDs will fail short of their expected lifetime. Similarly to some early CFLs, these products that fail early can easily give a bad reputation to other similar products.

Evolution of the Market [25]

There are essentially three different paths to market open to LED lighting solutions.

- New Construction: The most straightforward path to market for LED lighting is, of course, new builds. In this case, the lighting design of the building can be chosen to suit the characteristics LED fixtures. It is, however, the slowest evolving type of lighting as it depends on either builds in new locations, or old builds must be replaced by new ones. Since the number of fixtures per installation can be high, it can result in a very attractive volume per installation ratio.
- Replacement: The replacement market probably has the most opportunities for LED lighting, but it also has some very difficult issues to overcome, the most critical of which is the fact that it has to be compatible with the existing lighting interfaces. The LED replacement will have to provide the same quality of light (diffusion, brightness and colour temperature etc.), while being limited by the envelope (basic shape) and electrical interface of the bulb. On top of this, the replacement will also have to dissipate the extra conducted heat that is generated by LED lighting. This can be quite a daunting prospect, and sometimes compromises have to be made, usually either cost or quality can suffer.
- Retrofit: The retrofit market is possibly the most vibrant market for LED lighting at the moment. Unlike the new construction market, it does not depend upon new builds, and unlike the replacement market, it is not as restrictive in relation to having to be compatible with the existing lighting interfaces. When retrofits are undertaken in a building, generally all the fixtures of a particular type are replaced, which leads to some scope for altering the interface to suit the LED fixtures. Unfortunately, this can be quite a labour intensive process, which means the cost of the light fixtures themselves must be kept as low as possible in order to maintain a feasible payback time for the retrofit.

Emergence of a Dominant Design

An important milestone in the evolution of the LED will be the emergence of a dominant design, and thus the commoditization of the LED itself. Currently, LED design seems to be narrowing in on three distinct designs.

- High powered 1 mm^2 dies, designed to operate with a forward current of around 1000 mA. These LEDs output a very bright, directional light, and are quite useful in highbay and outdoor lighting applications.
- High powered arrays. These LED sources are based on multiple dies connected in a matrix (both in parallel and in series) and grouped together closely on a single board. Heat dissipation can an issue. These arrays are commonly used in highbay and outdoor lighting applications, but are also quite suited to recessed lighting replacements.
- Lower powered lighting strips. These LED sources are used when a softer, more even light source is required. They are made up of strips of low powered LEDs (usually somewhere between 10 and 40 in a strip) which output a more even and diffuse light than their high powered counterparts.

This process of narrowing in on these dominant designs follow the Utterback / Abernathy model of adoption. Industries begin with product innovation (can be taken as efficiency improvements), and as the industry matures, move onto process innovation (can be taken as a cost improvement). Below is a chart that tracks evolution of an industry though innovation (fluid phase, many competitors), through to optimization (transitional phase, fewer competitors) and onto commoditization (specific phase, reduced number of dominant competitors).

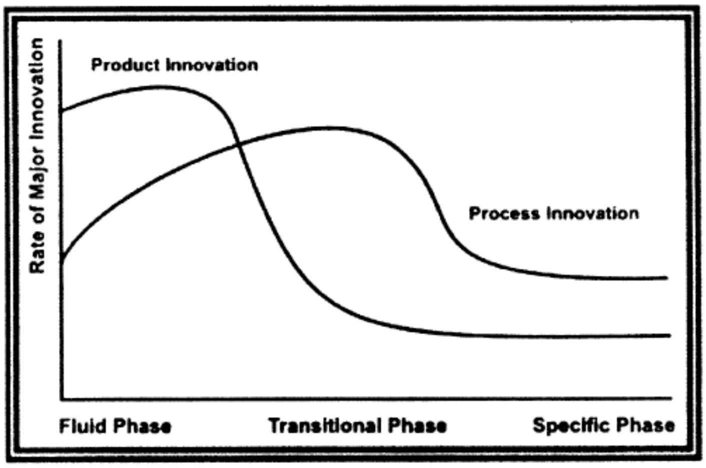


Figure 16 - Utterback/Abernathy model of adoption

Below is a version of this chart for the LED industry. The y-axis is percentage efficiency change per year (red line), and percentage cost change per year (blue line). As you can see, the industry is currently in the transitional phase, but will soon be maturing into the specific phase. The fixture industry will follow the LED industry in maturing into commoditization, but will invariably lag it by a number of years.

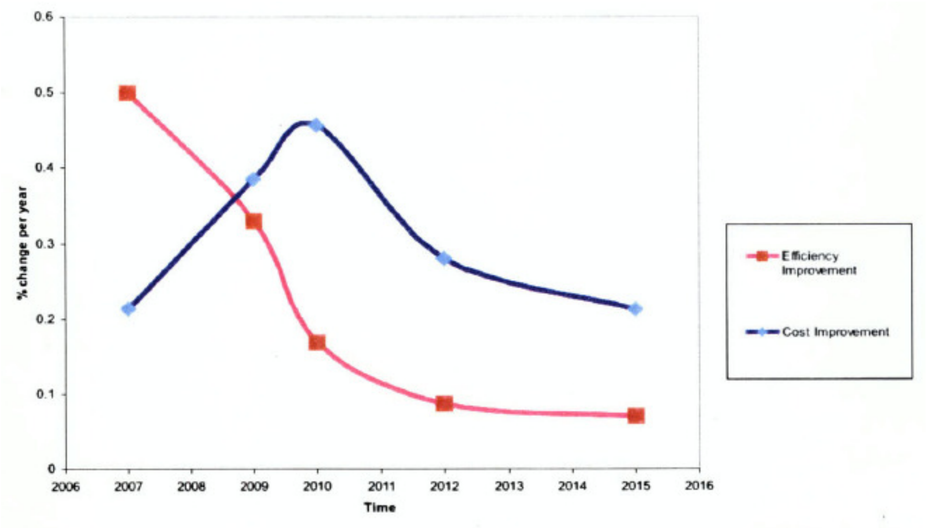


Figure 17 - Percent change in efficacy and cost of inorganic LEDs over time

Lighting Supplier Segmentation

Another important aspect of the lighting industry going forward is lighting supplier segmentation. The fewer dominant suppliers in the market, the shorter the path to a dominant design and commoditization. Currently in the lighting market, there are a few major companies that manufacture light bulbs, and many smaller companies that design and manufacture lighting fixtures.

LED lighting is a disruptive technology, and may completely alter this dynamic. Due to the long lifetime of LEDs, they cannot be considered replaceable in the same way that bulbs are. This has two important implications, the replacement market will quickly diminish, and LEDs will be sold as part of a complete fixture (as opposed to a replaceable bulb). Now both fixture and bulb manufacturers will have to learn what is required to design LED lighting fixtures, and they will also have to compete with new entrants to the market who are already experienced in LED design.

In this environment, many of the major players are attempting to vertically integrate their LED design and manufacturing capabilities, by either developing or purchasing all the required departments to manufacture complete LED fixtures (i.e. optics, LEDs, housing, drivers etc.). This means that in order to compete, the smaller companies will have to foster strong ties with others in order to be able to supply a complete modularized solution.

Conclusions

The aim of this preliminary report was to highlight the role that solid state lighting can play in demand side management in the future, their energy saving potential and their suitability for general lighting applications. The excellent efficacies of LEDs mean that LED lamps are already more efficient than many existing lighting technologies. With current U.S. Department of Energy roadmaps predicting that LED efficacies of 200 lm/W are attainable, LED lamps are set to be the most efficient form of artificial lighting in the coming years. Couple this with falling initial costs, and increasing versatility it is very likely that LED lighting will become the dominant form of artificial lighting for years to come.

The Excelsys portfolio has a range of products available to the user to provide a solution for whatever the application requirements may be. We have constant current, constant voltage, and dimmable constant current models available in an extensive power range. These start at 25 Watts and continue up to 300 Watts. A full catalogue of our LED drivers is available on request from sales@excelsys.com or salesusa@excelsys.com

References

[1] Intergovernmental Panel on Climate Change, "Climate Change 2007: The Physical Science Basis, The Summary for Policymakers," 2007.
[2] Heritage and Local Environment Department of the Environment, "Ireland. National Climate Change Strategy 2007-2012," ed, 2007.
[3] Commission of The European Communities, "An Energy Policy For Europe," ed, 2007.
[4] CBI Climate Change Task Force, "Climate Change: Everyone's Business," ed, 2007.

[5] P Bertoldi and B Atanasiu, "Residential lighting consumption and saving potential in the enlarged EU," 2006, pp. 21-23.

[6] IEA, *Light's Labour's Lost*, 2006.

[7] CJ Humphreys, "Solid-state lighting," *MRS bulletin,* vol. 33, pp. 459-470, 2008.

[8] Paolo Bertoldi, "Residential Lighting Consumption and Saving Potential in the Enlarged EU," 2006.

[9] SEAI, "Demand Side Management in Ireland," 2008.

[10] Dr Brian O Gallochoir & Emer Dennehy Martin Howley, "Energy in Ireland Key Statistics 2009," 2009.

[11] EMET (For Sustainable Energy Authority of Victoria), "The Impact of Commercial and Residential Sectors' EEIs on Electricity Demand," 2004.

[12] Wikipedia. (2010, *Light*. Available: http://en.wikipedia.org/wiki/Light

[13] Cary Eskow. Light Matters. Designing Illumination Systems With High-Brightness LEDs. *LightSpeed*.

[14] GE Lighting. (2010, *Spectral Power Distribution Curve*. Available: http://www.gelighting.com/na/business_lighting/education_resources/learn_about_light/distribution_curves.htm

[15] N Oi and H Takahashi, "Preferred combinations between illuminance and color temperature in several settings for daily living activities," 2007, pp. 214–215.

[16] LJ Sandahl, TL Gilbride, MR Ledbetter, HE Steward, and C Calwell, "Compact fluorescent lighting in America: lessons learned on the way to market," *Richland WA: Pacific Northwest National Laboratory,* 2006.

[17] E Engelhaupt, "Do compact fluorescent bulbs reduce mercury pollution?," *Environmental Science & Technology,* vol. 42, pp. 8564-8570, 2008.

[18] M. Granger Morgan and Fritz Morgan Ines Lima Azevado, "The Transition to Solid-State Lighting," *Proceedings of the IEEE,* vol. 97, 2009.

[19] Rob Lineback. (2006) Solid-state Lighting Set to Boost LED Growth. *LEDs Magazine*.

[20] U.S. Department of Energy, "Energy Savings Potential of Solid State Lighting in General Illumination Applications," 2010.

[21] U.S. Department of Energy, "Solid-State Lighting Research and Development Multi-Year Program Plan FY'09-FY'15," ed, 2009.

[22] Phillips Lumileds, "DR: LM-80 Test Report," 2010.

[23] DOE, "Energy Savings Potential of Solid State Lighting in General Illumination Applications," 2006.

[24] Osram, "Life Cycle Assessments of Illuminants," 2009.

[25] Ryan C Williamson, “Strategies for the Future of Lighting”, 2010

Excelsys Technologies Ltd. is a modern world-class power supplies design company providing quality products to OEM equipment manufacturers around the world. This is achieved by combining the latest technology, management methods and total customer service philosophy with a 20 year tradition of reliable and innovative switch mode power supply design, manufacture and sales. If there are any further points you wish to discuss from this paper please contact support@excelsys.com.